Quarterly Report 1

Covering the Period 1 May to 1 August 1973

STUDY TO DESIGN AND DEVELOP REMOTE MANIPULATOR SYSTEM

By: J. W. HILL A. J. SWORD

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
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SRI Project 2583

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ABSTRACT

This report describes human performance measurement techniques for remote manipulation tasks and remote sensing techniques for manipulators. For common manipulation tasks, performance is monitored by means of an on-line computer capable of measuring the joint angles of both master and slave arms as a function of time. The computer programs allow measurements of the operator's strategy and physical quantities such as task time and power consumed. The results are printed out after a test run to compare different experimental conditions.

For tracking tasks, we describe a method of displaying errors in three dimensions and measuring the end-effector position in three dimensions.

We also report progress on remote sensing systems based both on touch and distance sensing. The touch-sensing system uses proportional force sensors distributed over the remote hand to measure the overall force distribution of objects against the hand. The range sensor uses reflection from infrared light beams to identify the position of objects at a distance of a few centimeters to more than 20 centimeters in front of the hand.

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ILLUSTRATIONS

TABLES

I INTRODUCTION

This report describes continued progress toward the development of (1) measurement techniques and tasks for evaluating man's manipulative performance and (2) remote sensing and display techniques to augment man's manipulative skills. Much of the work is a further development of the manipulator system previously described.[1]*

To study human performance both in the time delay situation and situations using different displays, manipulators, and controls, the pilot experiments of Sections II and III were carried out. The pilot experiments provided a data bank for the logging and analysis programs developed in Section V; the new data analysis techniques are being tested out and debugged. Section V describes the experimental configuration for carrying out both compensatory and pursuit tracking tasks in space. With the multicoordinate tracking program previously described,[1] it will be possible to measure describing function remnant spectra and root-mean-square (rms) tracking errors.

For automatic control of remote manipulators and to enable man to have better manipulative skills, certain features of the remote environment must be sensed. Sections VI and VII describe the continued development of sensors for this purpose. Development of the touch sensing system begun under NASA-SNSO support[2] is being continued here. The goal is to develop a touch sensing and display system that gives man the "feel" of the remote objects he is handling.

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*References are listed on page 32 of this report.

II PILOT TACTILE DISPLAY EVALUATION

Experiment I approximates the experiment described in Appendix F of Reference 1. The only modification of the experiment was to perform eight repeated pick-up attempts instead of ten. Since performance seemed to be improving as the experiment progressed, the entire experiment was repeated a second time in reverse order. We hope that the additional data can be used to plot learning curves and that both learning rates and ultimate performance levels can be used to differentiate between experimental conditions.

Performance measurements consist of both the task time for each run as measured by a stopwatch and the number of fumbles or drops occurring during each experimental condition. In all conditions except the visual sensor display, the performance monitor package described in Section IV of this report was used.

At the present time the data from the experiment are being reduced and prepared for plotting, analyses of variance, and other statistical tests.

III PILOT TIME DELAY EXPERIMENT

A. General

This experiment investigates changes in the operator's manipulation strategy as the transmission delay is varied over a wide range. The approach is to obtain a bank of human performance data using the data-logger described in Section IV of this report and then to experiment with several performance indices to find those that best characterize the changes in strategy from a continuous strategy to a move-and-wait strategy as the time delay increases from zero to well over one second. The areas of particular interest are numbers of moves, relations of arm motion to decisions to move, and descriptions of the complex move-and-wait strategy. The measurements made by the off-line analyses of Section IV represent an initial attempt to obtain such indices. The results of this pilot time-delay experiment will probably suggest other still more pertinent manipulation parameters to be obtained while an experiment is being carried out.

B. Method

The experiment is arranged in a 3 x 5 x 2 factorial design, as shown in Figure 1. Each cell in the design represents a performance characteristic measured on two subjects in eleven repetitions of the task.

The experiment variables are (1) manual control mode, (2) transmission delay, and (3) replication, as indicated in Figure 1. The manual control mode is varied by use of either the Rancho master brace or a bank of six potentiometers. Transmission delays from zero to ten seconds are provided in both control conditions, and in all replications by using

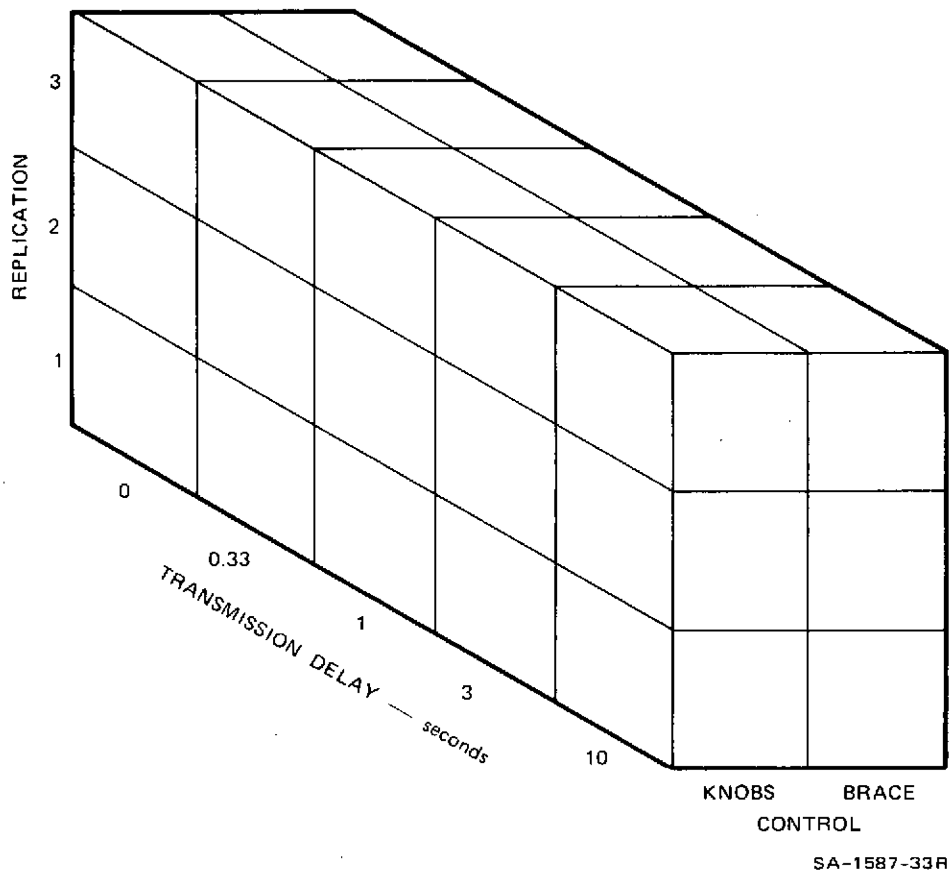

FIGURE 1 DESIGN OF THE PILOT TIME DELAY EXPERIMENT

the 30-Hz delay line simulation described in Section II of Reference 1. Direct viewing was used and audio cues were provided in all experimental cases.

1. Apparatus

The Rancho arm and computer augmented control system described in Section II of Reference 1 were used for this experiment. The control modes were solely manual, master-slave modes. No sensory feedback other than direct vision was provided to the operator. The task was to pick up a block randomly placed within the arm workspace and deposit it in a small container.

2. Subjects

Two male subjects, LM and SM, were used for this experiment. Both had considerable experience in using the manual control modes for a pick-up task. However, neither subject had ever attempted the task with a transmission delay.

3. Procedure

The on-line performance logger (see Section IV) is started when the end effector passes through a plane one-foot above the table on the way down to grasp the object. The task is complete when the object is grasped and deposited in the receptacle, and the end effector moves up out of the workspace. Then the performance logger stops.

In a single replication, each subject performed 10 runs consisting of 11 repetitions each. Five runs, each corresponding to one of the transmission delays, were performed using each of the two control modes. This sequence was repeated three times for each subject. In all, each subject made 333 individual pick-up attempts.

C. Analyses Underway

1. Performance Measures

A $5 \times 3 \times 2 \times 2 \times 11$ analysis of variance of each of the performance indices determined by the performance monitor (Section IV) is being carried out to determine their relative importance in differentiating between test conditions.

2. Movement Time Distribution

We plan Chi-square analyses to determine whether the movement time distribution (Section IV) changes significantly with varying transmission delay and control input.

IV EXPERIMENT ANALYSIS TOOLS

A performance monitor package was created to study (1) the complex move-and-wait strategy and (2) the movement and waiting times with different transmission delays, different visual and tactile feedback, and different arms. The performance monitor can measure and tabulate the movement and waiting times with considerably greater accuracy and reliability than can a human observer with a stopwatch.

The performance monitor package consists of an on-line program for data logging and several off-line programs for numerical analysis. During the experimental runs, a high-speed disk memory logs on-line data. Upon completion of the experiment, it is copied to magnetic tape for permanent storage. Different off-line programs are used to search the log and to extract the desired performance indices. This section gives the description of the components of this performance measuring system.

A. Using the On-Line Performance Logger

The control codes available to the experimenter for accumulating and logging data are shown in the control tree of Figure 2. A typical control sequence for logging two replications of an experiment is shown in Figure 3, where information typed by the operator is underlined.

B. Operation of the On-Line Performance Logger

The on-line performance logger detects the beginning and end of moves by using derivatives of the individual joint angles.* In total, 14

*An alternative method of detecting moves based on a calculation of instantaneous joint velocity is being investigated.

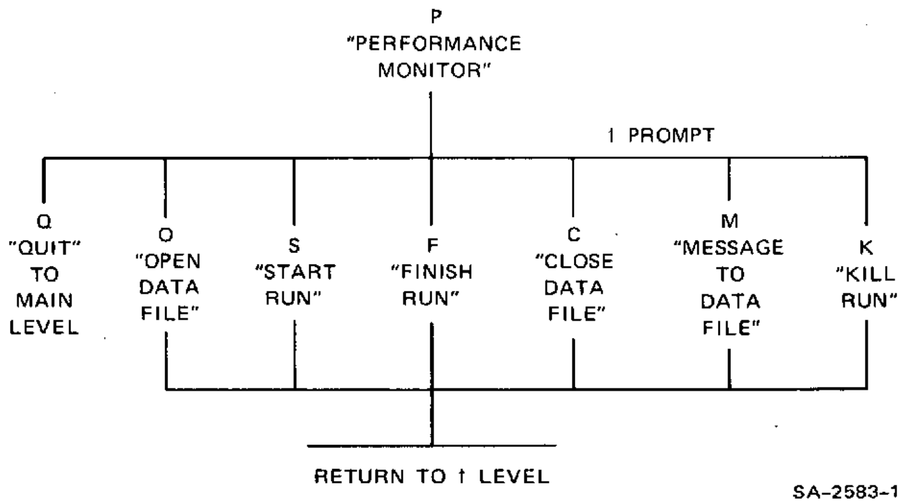

FIGURE 2 COMMAND STRUCTURE FOR THE ON-LINE PERFORMANCE LOGGER

↑ OPEN * PFILE ENTER NAME, DATE ↑ SUBJECT 1, 6/10/72 TEST 2	Logging In
↑ START ↑ FINISH	Replication 1
↑ START ↑ KILL FINISH ↑ MESSAGE * BLOCK FELL TO GROUND, TRY AGAIN	Replication 2 Unsatisfactory
↑ START ↑ FINISH	Replication 2 o.k.
↑ CLOSE ↑ QUIT	Logging Out

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FIGURE 3 TYPICAL PERFORMANCE LOGGER CONTROL SEQUENCE derivatives (seven master and seven slave joint angles) are updated and digitally filtered every 1/30 of a second. If any of the master or slave joints exceeds a predetermined threshold for motion during a 1/30-second period, a note of the fact is made in separate master and slave move detection queues. These queues (software shift registers) record whether or not a move was detected during 12 successive 1/30-second intervals. From these intermediate data, decisions are made to determine whether a master or slave move has begun or ended. The flow chart of the performance monitor is given in Figure 4. The criteria for detecting the beginnings and ends of moves that have proved successful are defined below:

- Move criterion--A move begins when the velocity threshold is exceeded during the current 1/30-second interval and will be exceeded on five of the next 12 intervals.
- Done criterion--A move is done when the velocity threshold is not exceeded during the current interval and will not be exceeded more than once in the next 12 intervals.

Two total task measurements are also obtained. The on-line program counts the number of 1/30-second intervals taken to complete a task and logs the total at the end to permit the calculation of task duration. Additionally, it accumulates the current delivered by the 24-volt servo power supply every 1/30 second and logs the total at the end of the run to permit calculation of the total energy consumed. The first three numbers following the "/" symbol are the triple precision accumulation of the current, and the next two are the double precision accumulation of the task time.

Messages entered during the run are printed directly in the data log. Entering the "kill" message during a run causes a "?" symbol to print out on the data log and further logging to cease. The meanings of the various symbols used in the data log are given in Table 1. An example of the data log for run Number 1 of Subject SM is given in Figure 5. The first number and symbol, 0036 >, represents the one-second time delay in thirtieths of

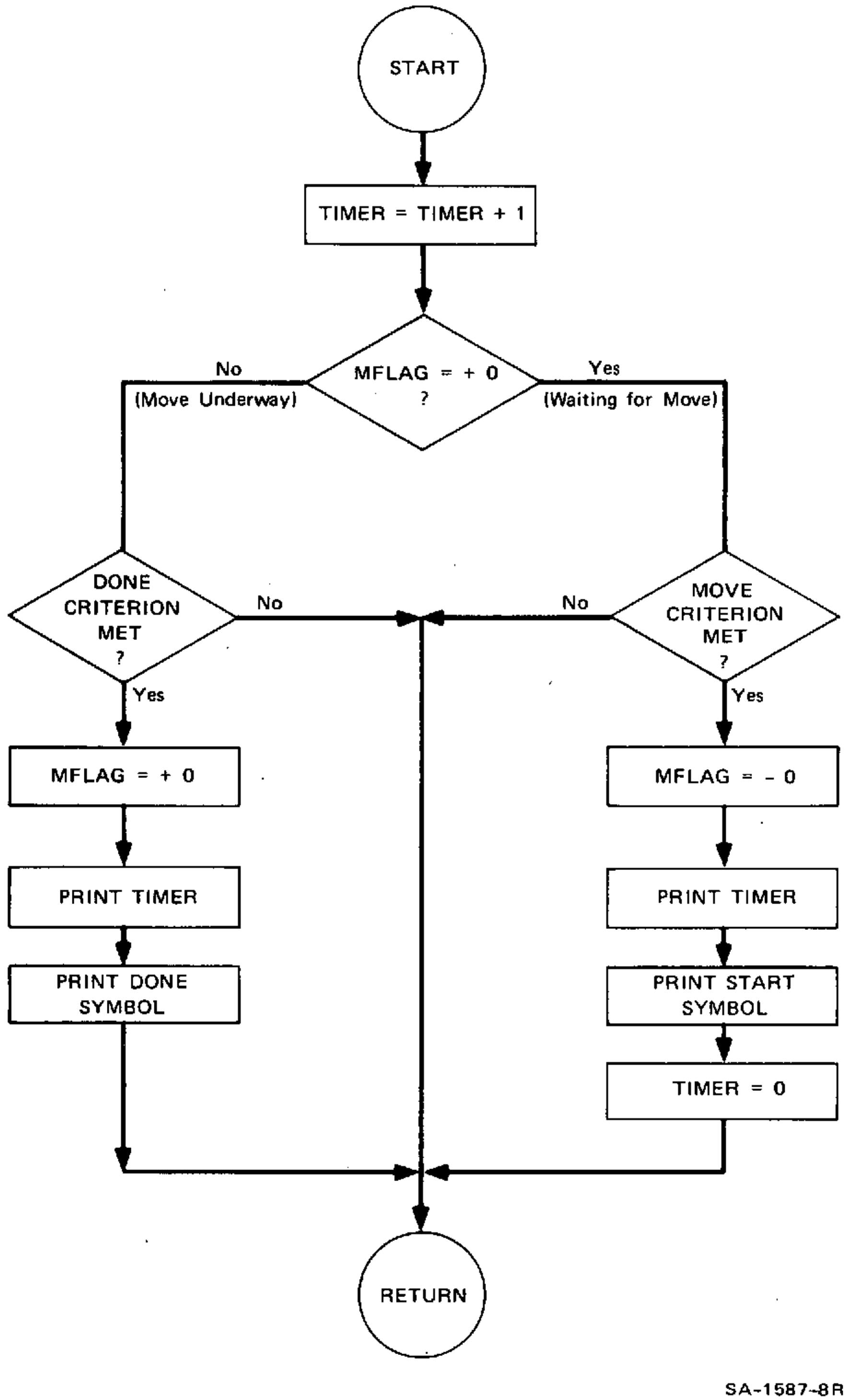

FIGURE 4 PERFORMANCE LOGGER MOVE DETECTION ALGORITHM

Table 1

SYMBOLS USED BY ON-LINE PERFORMANCE LOGGER

Symbol	Meaning
$	Master move detected, counter = 0
#	Master move ended
@	Automatic move initiated, counter = 0
↑	Slave move detected
•	Slave move ended
"carriage return"	Counter before automatic or manual move begun
>	Time delay
/	Power and time printout follow
?	Kill feature initiated; ignore data from this run
*	Identifying message follows
"end of record"	End of replication
"end of file"	End of run

```
*SUBJECT SM BLØCK PICKUP AND DRØP
0036>0036
0000$0043↑0052#0110•0111
0000$0020#0043↑0063•0073
0000$0017#0043
0000$0000↑0024•0043↑0046#0077
0000$0011•0027#0106↑0146•0157
0000$0043↑0254#0316
0000$0001•0034#0042↑0100•0154
0000$0017#0046
0000$0000↑0020#0066
0000$0004•0024#0045↑0060
0000$0010•0040↑0042#0101•/0000 0014 2277 0000 1626
```

FIGURE 5 EXAMPLE OF DATA LOG

a second (in octal). On the last line, the first three numbers after the "/" are the accumulated current, and the next two are the accumulated run time in thirtieths of a second (octal).

C. Off-Line Timing Program

A computer program for obtaining particular performance figures from the data log has been developed. The indices obtained and the means of obtaining each of them is given in Table 2.

Table 2

PERFORMANCE INDICES

Symbol	Definition	Method of Obtaining Measurement
N_m	Number of master moves	Counting the number of "#" symbols
N_s	Number of slave moves	Counting the number of "." symbols
E_t	Task energy	$\frac{V}{Rate}$ times the current accumulator
T_t	Task time	$\frac{1}{Rate}$ times clock accumulator
T_m	Total moving time	$\frac{1}{Rate}$ times sum of master move times; the master move time for each move precedes the "#" symbol.
R_m	Moving ratio	T_m divided by T_t
$\bar{M}_m$	Mean movement time	T_m divided by N_m

The printout from the timing program for two subjects is shown in Figure 6. Each of the data files analyzed consists of 11 replications of a pickup and drop task carried out with a time delay of one second. The performance indices are printed out in the same order as they are defined in Table 2. Times are in seconds and energy is in kilowatt seconds.

D. Off-Line Histogram Program

In order to investigate changes in the operator's strategy under experimental conditions such as time delays, we wrote a program to obtain the distribution of move times. The algorithm is essentially that of the well-known "pulse-height analyzer."

In the move-time analyzer there are 51 bins for accumulating counts. When a master move (indicated by a "#" in the data log) is found, the appropriate bin is incremented by one to count the move. The first bin is for move durations of 1/30, 2/30, and 3/30 second (0.03 to 0.1 second); the second bin is for durations of 4/30, 5/30, and 6/30 second (.13 to .2 second); and so the bins continue to the highest bin which accumulates all moves greater than 150/30 seconds (5 seconds). After all the desired data logs are searched, a printout of the bins can be requested.

An example of using the program and its resultant output is shown in Figure 7. Here the data analyzed are the same as those of Figure 6. As Figure 7 indicates, there were 22 test runs and 447 master moves; the mean value of the ensuing distribution is 1.257 second. Following the totals is printout of the bin totals. The first number on each line is the bin count, and the second is the lower bound of each bin in seconds. The bin counts are illustrated graphically by printing one space for each move in the bin followed by an asterisk.

As in Figure 7, whenever a moderate number (447) of moves is tabulated in this way, the distribution is noisy. For purposes of comparing two

••••••••••••••••••••••••
EXAMIN*SM3

SUBJECT SM BLØCK PICKUP AND DRØP
TIME DELAY = 1.00

RUN	M-MØVES	S-MØVES	ENERGY	TIME	MTIME	MRATIØ	MBAR
1	11	10	1.41	30.5	13.9	.456	1.26
2	11	12	1.91	35.4	13.4	.380	1.22
3	10	8	1.21	27.4	12.0	.436	1.20
4	50	41	5.58	118.4	47.4	.400	.94
5	20	17	3.29	58.0	27.3	.471	1.36
6	9	8	1.55	30.4	16.3	.536	1.81
7	27	24	3.69	69.0	32.7	.474	1.21
8	23	17	3.77	63.5	29.4	.464	1.28
9	10	8	1.28	25.7	10.8	.419	1.08
10	8	5	1.35	29.2	16.9	.578	2.11
11	52	44	8.41	159.1	68.2	.428	1.31
AVG	20.99	17.63	3.04	58.8	26.2	.446	1.24

••••••••••••••••••••••••
EXAMIN*LM3

SUBJECT LM BLØCK PICKUP AND DRØP
TIME DELAY = 1.00

RUN	M-MØVES	S-MØVES	ENERGY	TIME	MTIME	MRATIØ	MBAR
1	50	46	6.44	130.8	66.4	.507	1.32
2	10	13	1.41	30.7	17.0	.552	1.70
3	13	9	1.40	28.3	11.1	.390	.85
4	29	29	4.59	97.7	30.9	.316	1.06
5	16	14	1.84	37.7	15.6	.415	.97
6	27	22	3.48	68.4	38.0	.555	1.40
7	10	6	1.46	29.9	16.4	.548	1.64
8	19	16	2.34	46.1	21.4	.464	1.12
9	12	11	1.72	35.3	17.9	.508	1.50
10	9	9	1.52	30.9	17.6	.568	1.95
11	21	16	2.37	52.0	20.9	.402	.99
AVG	19.64	17.36	2.60	53.5	24.8	.464	1.26

••••••••••••••••••••••••

FIGURE 6 PRINTOUT OF TIMING ANALYSIS

```
HISTOGRAM FROM*SM3
DELAY = 1.00
...........AND FROM*LM3
...........AND FROM*H\ E

      22 RUNS     447 M-MOVES   1.257 SEC=MBAR


--------+---------+---------+---------+---------+---------+---------+---*
  0  .0 *
 13  .1             *
 27  .2                           *
 29  .3                             *
 37  .4                                     *
 27  .5                           *
 37  .6                                     *
 26  .7                          *
 29  .8                             *
 29  .9                             *
 24 1.0                        *
 19 1.1                   *
 20 1.2                    *
 14 1.3              *
 14 1.4              *
 15 1.5               *
  9 1.6         *
  5 1.7     *
  8 1.8        *
  2 1.9  *
  5 2.0     *
  1 2.1 *
  2 2.2  *
  4 2.3    *
  1 2.4 *
  3 2.5   *
  3 2.6   *
  1 2.7 *
  0 2.8 *
  2 2.9  *
  3 3.0   *
  4 3.1    *
  5 3.2     *
  2 3.3  *
  2 3.4  *
  1 3.5 *
  1 3.6 *
  2 3.7  *
  0 3.8 *
  1 3.9 *
  3 4.0   *
  1 4.1 *
  1 4.2 *
  1 4.3 *
  2 4.4  *
  0 4.5 *
  0 4.6 *
  1 4.7 *
  1 4.8 *
  1 4.9 *
  9 5.0         *
--------+---------+---------+---------+---------+---------+---------+---*
```

FIGURE 7 USE AND OUTPUT OF THE HISTOGRAM PROGRAM distributions to see how they differ, it is desirable to smooth the distribution mechanically rather than by hand. As an option, the user may apply the smoothing function

$$S_i = \tfrac{1}{4} C_{i-1} + \tfrac{1}{2} C_i + \tfrac{1}{4} C_{i+1}$$

which causes each bin in the smoothed function S_i, to contain half the counts in the same bin of the original function, C_i, and one-quarter the counts in each neighboring bin, C_{i+1} and C_{i-1}. The impulse response of this smoothing function is shown in Figure 8, and the results of applying it to the distribution obtained in Figure 7 are shown in Figure 9.

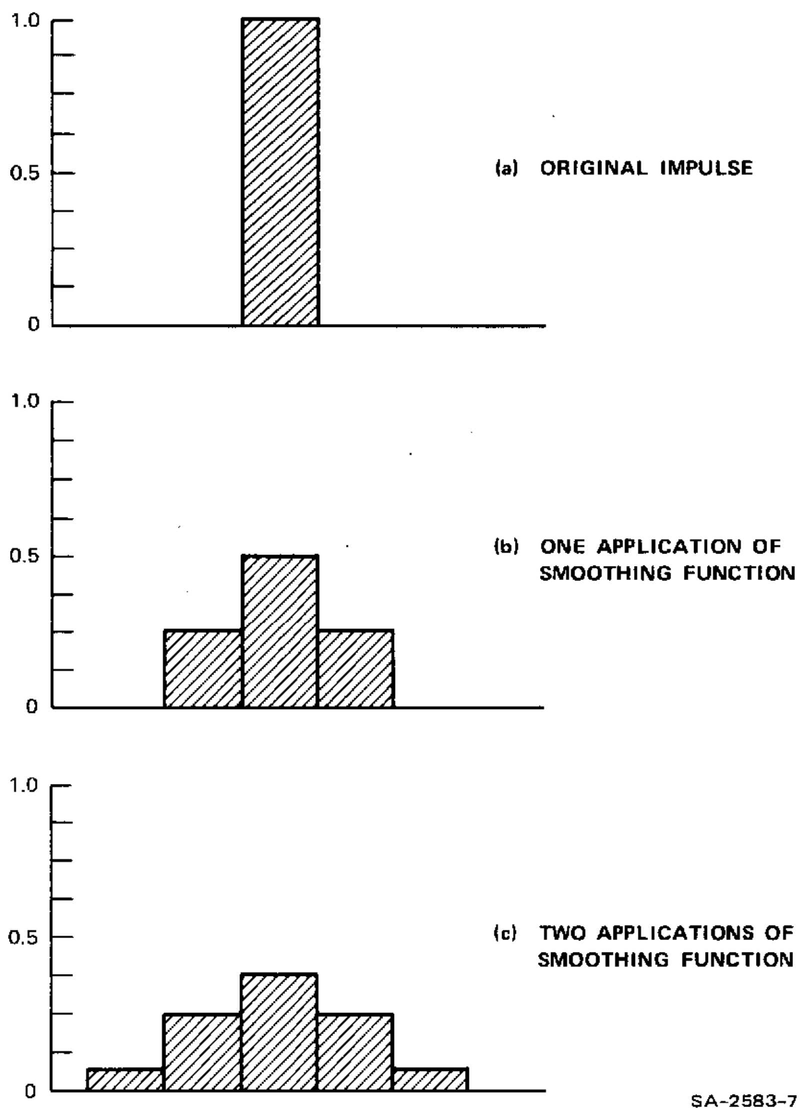

FIGURE 8 IMPULSE RESPONSE OF SMOOTHING FUNCTION

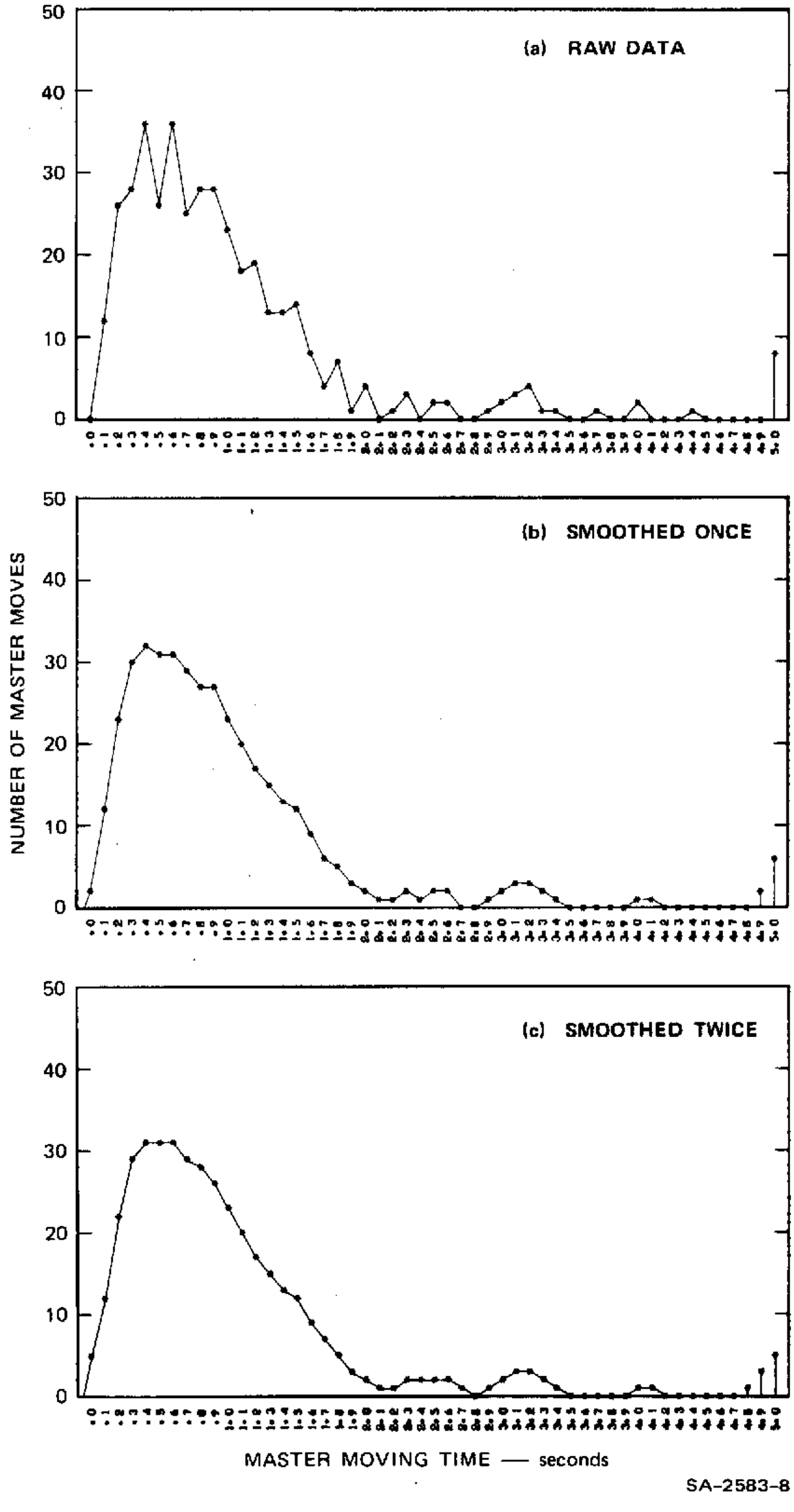

FIGURE 9 EFFECT OF SMOOTHING ON DISTRIBUTION OF MASTER MOVING TIMES

V TRACKING

A. Three-Dimensional Compensatory Display

In order to do tracking experiments, where the operator is required to trace a path in space, a three-dimensional display is required. The operator must be able to look at the display and quickly assess his position error along X, Y, and Z coordinates.

A display suitable for this task consists of a movable circle and dot on an oscilloscope screen and a set of fixed, cross lines as shown in Figure 10. The circle and dot can quickly be visualized as an arrow pointing either into or out of the oscilloscope screen. With X and Y errors, both the circle and dot move left and right or up and down in unison; with Z errors the circle moves up and down with respect to the dot. A photograph of the actual display as seen on the scope screen is shown in Figure 11.

The circuitry used to produce the display is shown in Figure 12. Command inputs for the three coordinates are generated by the computer; response inputs for the three coordinates come from three position-sensing potentiometers that monitor the position of the manipulator end point; error outputs go to the computer for on-line analysis. The 200-Hz multivibrator drives two field-effect switching transistors, causing the deflection outputs to follow alternately the X and Y errors directly or the X and Y + Z errors with an AC perturbation generating the circle.

This display can also be used to present two-dimensional, pursuit tracking tasks (the circle in the command position and the dot representing the operator's actual position). By commanding the circle to move

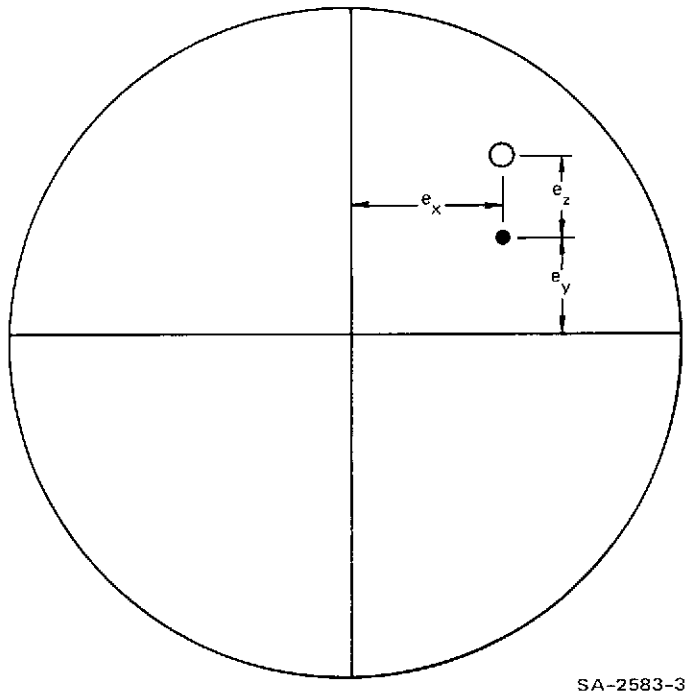

FIGURE 10 TRACKING DISPLAY

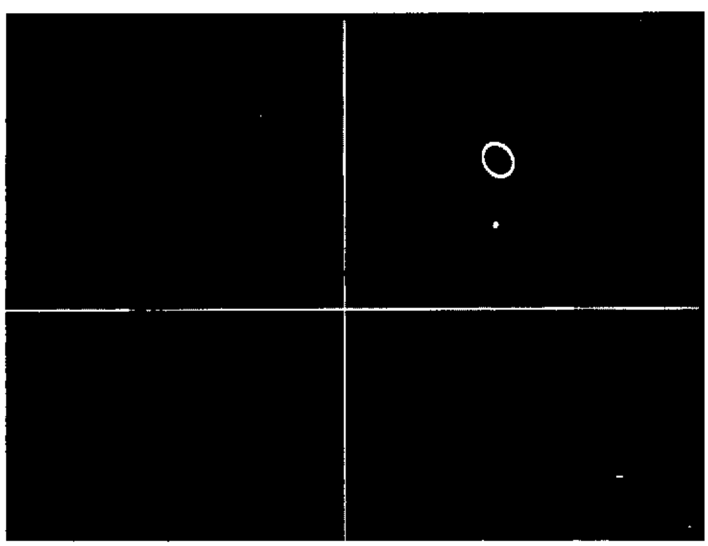

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FIGURE 11 PHOTOGRAPH OF TRACKING DISPLAY

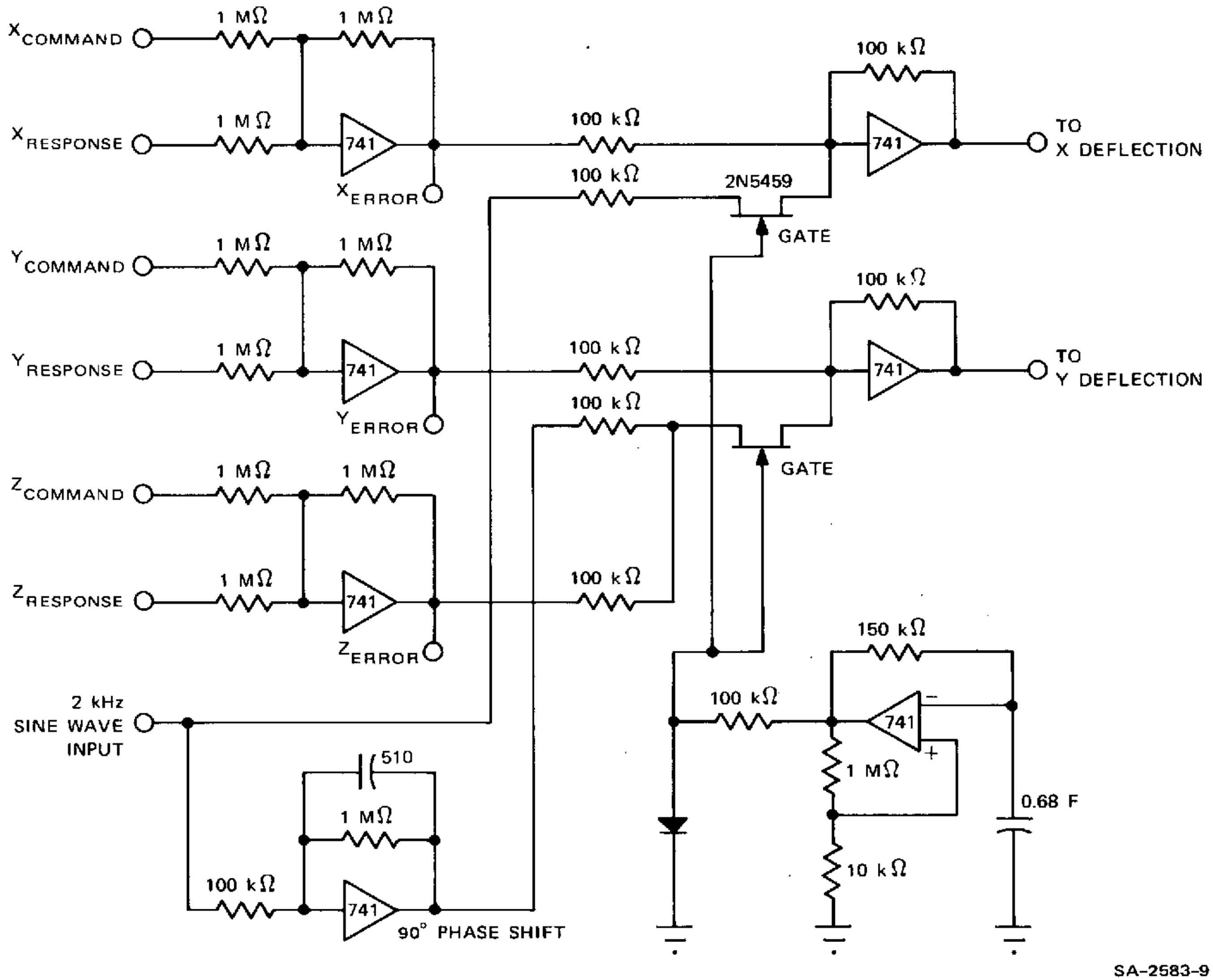

FIGURE 12 DISPLAY GENERATION ELECTRONICS

along a prescribed path, many different types of tasks can be simulated in the laboratory.

B. Three-Dimensional Position Sensing

In order to measure end-effector position, we designed a position sensor. Three of these sensors can be mounted in line with the three orthogonal axes (one sensor per axis). Each is attached to the end-effector via a control string. This is illustrated in Figure 13.

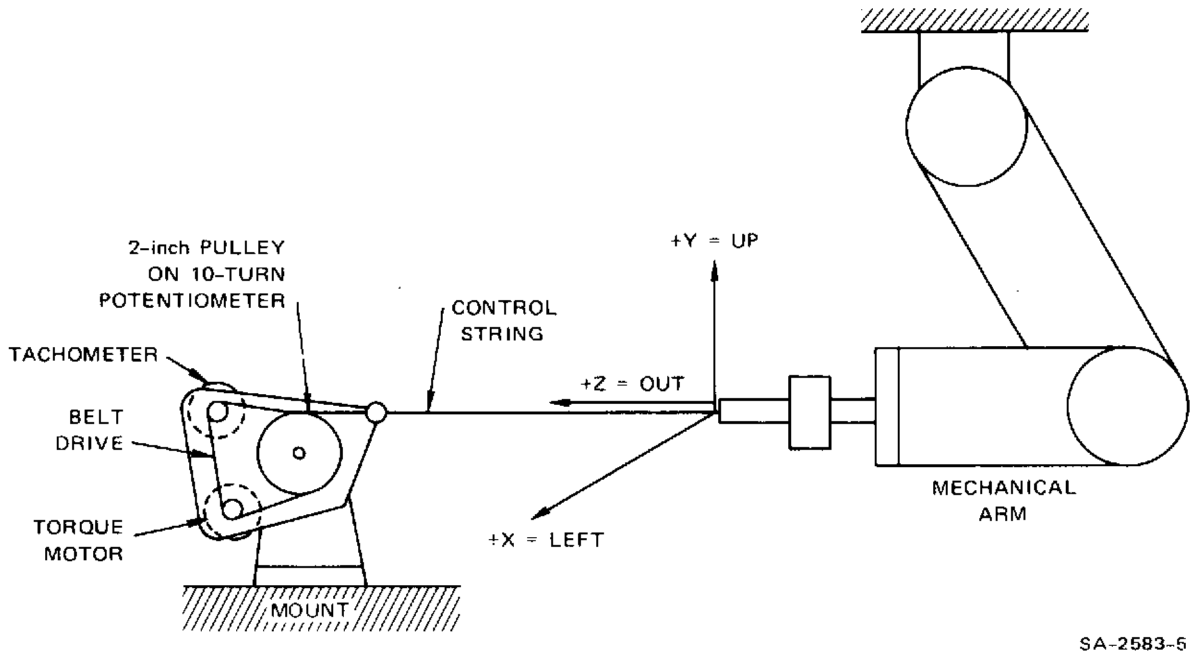

FIGURE 13 MEASURING THREE COORDINATE POSITION OF THE END EFFECTOR
(Only the Z-Axis Sensor is Shown)

The sensor itself consists of a two-inch diameter pulley attached to the shaft of a ten-turn potentiometer. The control string is attached to this pulley, enabling the sensor to determine position over a range of approximately 6 feet.

The control string is provided with a constant return force by a direct-current motor acting as a negator spring. The motor is coupled to the pulley via a belt drive.

In order to provide a velocity measurement in each of the three directions, a tachometer is mounted on the belt drive. The use of three velocity signals rather than six joint angles as input to the performance logger might considerably simplify the performance monitor software.

In addition, each sensor has a suction-cup base and movable and fixed control string guides to facilitate mounting. The position and velocity sensor is illustrated in Figure 14.

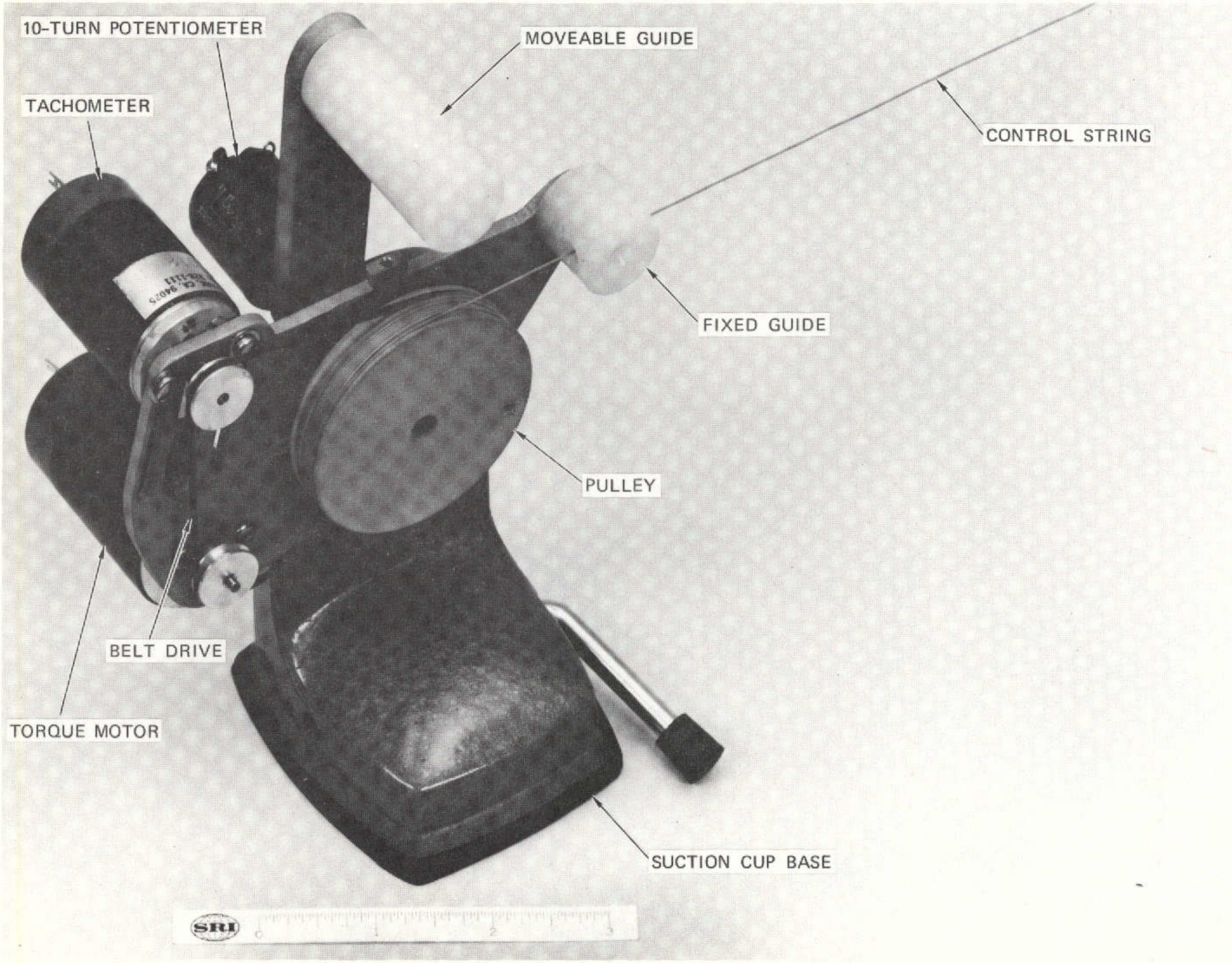

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FIGURE 14 POSITION AND VELOCITY SENSOR

VI TOUCH SENSING AND FEEDBACK SYSTEM

A. Background

During the period from 15 May to 15 November 1972, SRI proceeded with the development of a touch sensing and feedback system for the Space Nuclear Systems Office under Contract SNSN-63. The goal of this work was to design a system to provide, through a teleoperator, the touch information normally used by man in directly manipulating objects with his hands. Although Contract SNSN-63 was prematurely halted because the Space Nuclear Systems Office was closed, SRI had already completed the design of a set of sensorized tongs that can be fitted to the Navy arm.[3]

The previous work included (1) an overall design of a touch feedback system, (2) a selection of a sensor system based on bench-top tests, and (3) a selection of actuator systems based on bench-top tests, and (4) the design of a set of tongs based on results of 1 and 2. To date, we have built the pair of tongs and designed and almost completed the wrist and links to control the tongs. The results of this previous project and the adaptation of the system to the NASA-Ames arm are given in integral form for the first time in this report.

B. Tactile Feedback Considerations

Designs for a touch sensing system should consider (1) individual sensors and actuators, (2) the optimum encapsulation of the sensors in the end-effector, and (3) the arrangement of particular sensors on the tongs. The handgrip of the controller should serve the purposes of (1) providing a handle for transmitting six degrees of force to the arm controller, (2) displaying tactile quantities to the hand, and (3) providing one degree of freedom for opening and closing the end-effector. The integration of the important touch quantities into this control situation is shown in Figure 15.

Based on our feasibility studies (surveys of sensor and actuator technologies[2]) and the requirement of fitting the system to the Navy end-effector[3] and the MIT hand controller,[4] we have several recommendations for a tactile sensing system.

Primarily, it should convey two types of touch information to the human operator. One of these is contact or touch with a high spatial resolution based on a matrix of sensors on the jaw surfaces and a corresponding matrix of position reproducing actuators on the palmar surfaces of the human finger and thumb. The other type is contact or touch with low resolution for relaying touch quantities from the exterior of the end-effector to the man's hand as force reproducing actuators on the backs, sides, and tips of the human finger and thumb.

The high resolution system should have at least a 3 $\times$ 6 matrix of sensor buttons that cover the end-effector gripping surfaces almost completely. The low resolution system should have two sensitive surfaces (uniformly sensitive to force over the entire surface) on each exterior surface of the tongs.

Eventually, two commonly used prehension quantitites, force feedback and slippage feedback, should be included in a tactile sensing system. The role and implementation of these quantities is suggested in Figure 15 and implementation of them into the system would give man nearly complete "feel" of the remote environment.

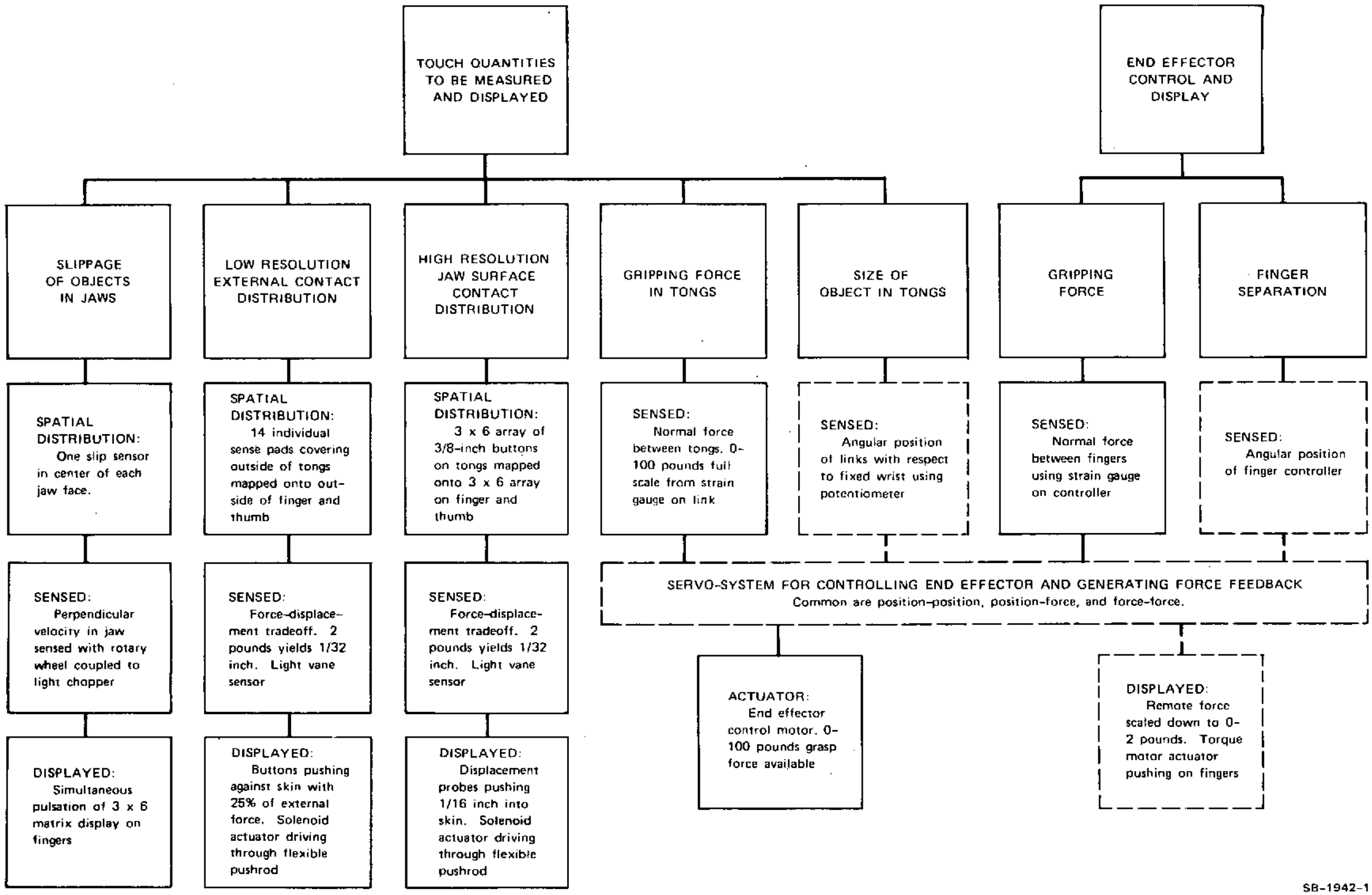


FIGURE 15 SENSING, CONTROL, AND DISPLAY OF TACTILE INFORMATION. Touch quantities commonly used by man in prehension are sensed on the end effector and anthropomorphically displayed on the hand controller. Dashed boxes are not to be considered in this study.

C. Selection of Touch Sensors

After a survey of sensing mechanisms and bench tests was conducted, an optomechanical sensing scheme was selected. The system is simple, both electrically and mechanically, and it can be very rugged. It consists of a light-emitting diode (L.E.D.), an optical shutter, and a phototransistor, as shown in Figure 16. As the light vane is pushed down, a rectangular aperture opens permitting light to fall on the phototransistor. The amount of light permitted to enter is directly proportional to the deflection of the vane.

The compact design of the shutter linked to a circular sensing pad on the surface of the end-effector is shown in Figure 17. A compliant washer (or spring) between the body of the tongs and the sense pad converts external force to deflection. By varying the compliance of the washer, the sensor can be adjusted to have full-scale output for applied weights from two grams to many kilograms.

D. Selection of Actuators

The survey of actuators for providing tactile stimulation to the operator's hand clearly suggested that rotary solenoids were best for this application. A bench-top design with rotary actuators and push-button stimulators is currently being used to develop tactile stimulators for both the high- and low-resolution systems. Another viable possibility being considered is that of using miniature torque motors with a rotary-to-linear displacement converter. A particular problem at this stage is the design of the push-rod mechanism that couples actuators and push-buttons.

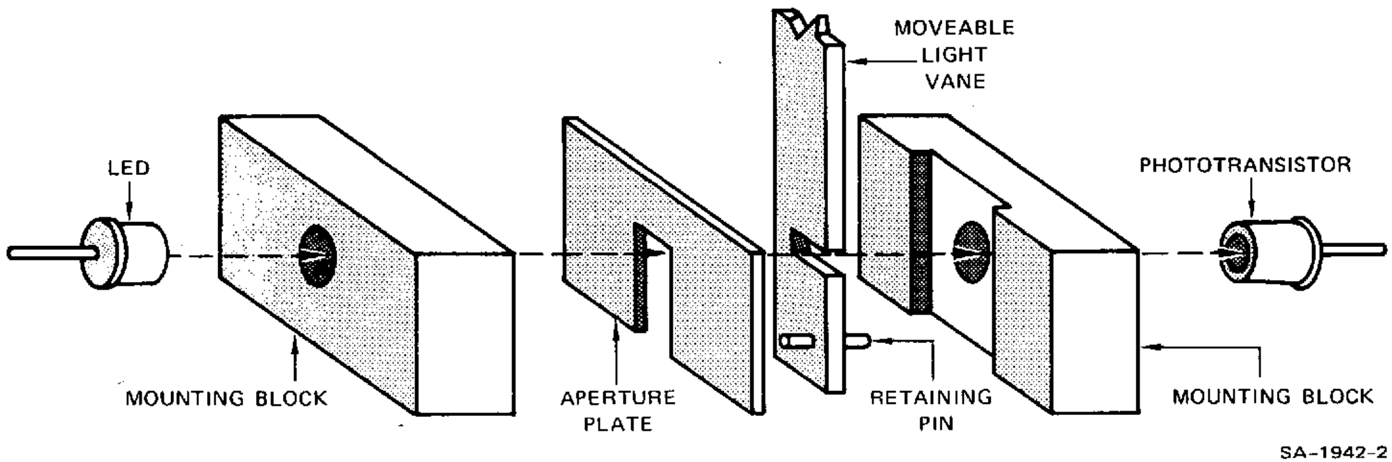


FIGURE 16 EXPLODED DRAWING OF SHUTTER

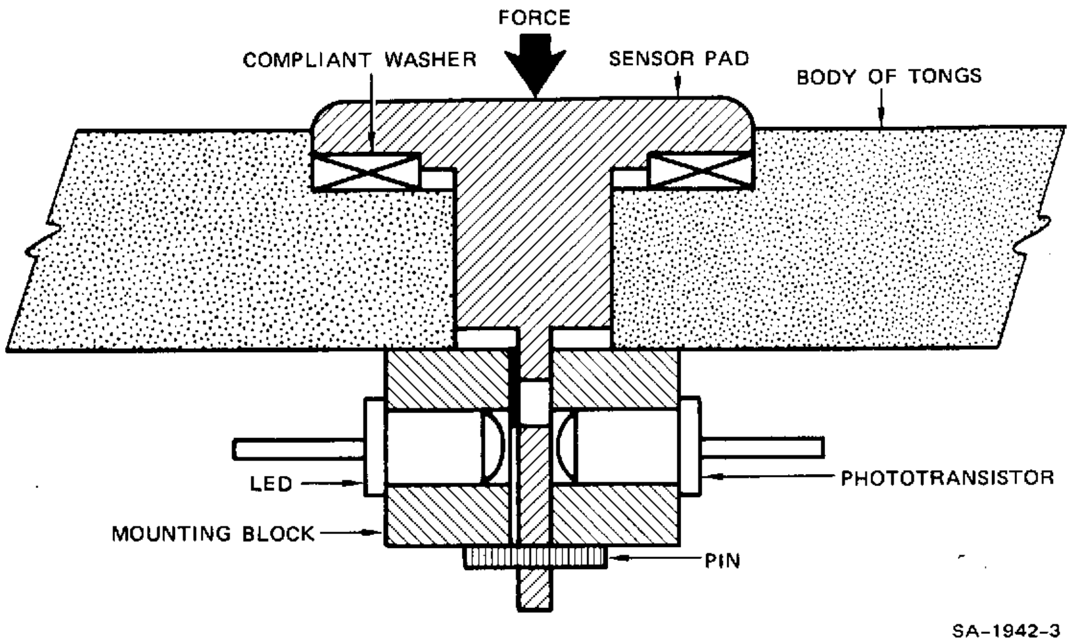


FIGURE 17 CROSS SECTION OF SENSOR WITH COMPACT SHUTTER

E. Hand Design

To experiment with and evaluate touch sensors in a working control system, an end-effector has been designed and partially constructed. The end-effector consists of drive motor, housing, and links to support and control the sensorized tongs designed for the Navy hand.[3] Preliminary measurements indicate that the sustained gripping force is 20 pounds and that the time to close the hand from an open position is 0.5 second. The speed and force characteristics were chosen to match the tongs to the NASA-Ames arm. Even higher opening and closing speeds may be necessary to allow the operator to effectively sense and control touch information fed back to him.

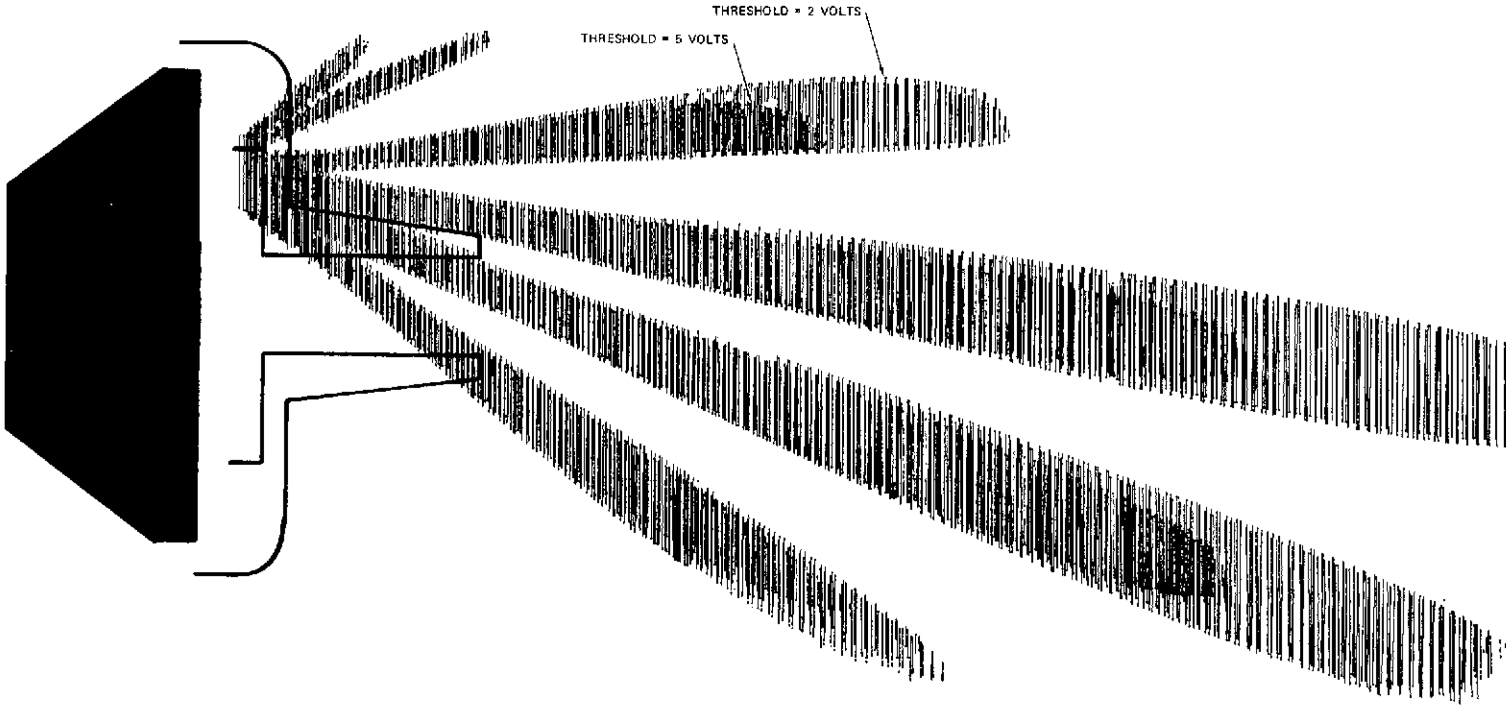
During the next quarter the hand should be completed, and we will make available a full description complete with a series of photos and sketches.

VII INFRARED POSITION SENSOR

During this quarter we have built a set of circuits to drive the sensor described in Appendix A of Reference 1 for bench-top testing. The circuitry is undergoing change and will be described at a later date. Experiments with the system include determination of (1) optimum focus and maximum strength of the light beams and (2) optimum focus and maximum receptivity of the phototransistor "eyes."

In order to make these measurements, we mounted the infrared position sensor on one edge of an XY plotter table. The movable carriage used a raster scan to search the area in front of the sensor. By mounting a light sensor or emitter on the movable carriage and controlling the up-down position of the pen from the detector output, we plotted field strengths.

An example of such a field-strength plot is given in Figure 18. Here a phototransistor with a small window (1-mm diameter) was swept slowly through the field on a raster scan. The period of the vertical sweep is about 10 seconds,and that of the horizontal sweep is about 10 minutes. The plot of Figure 18 reveals that two side lobes (not designed into the light-emitting system) are present at the top of the picture, and that the image plane of the light emitters is 2.2 inches in front of the sensor housing. Using these procedures it should be possible to map and control the receptive areas of the position sensor for best use in manipulation tasks.



SA-2583-10

FIGURE 18 FIELD STRENGTH PATTERN OF INFRARED LIGHT SOURCES

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3. A. B. Rechnitzer and W. Sutter, "Naval Applications of Remote Manipulation," paper presented at the First National Conference on Remotely Manned Systems, California Institute of Technology, Pasadena, California (September 1972).

4. __________, "Development of Multi-Moded Remote Manipulator Systems," Quarterly Progress Report 5, NASA Contract SNPN-54, Charles Stark Draper Laboratories, Massachusetts Institute of Technology (July 1972).